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Propulsion and Auxiliary Systems Department  
Research & Development Report

### Use of Radiation Efficiency in Noise Control Engineering

by

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## ABSTRACT

The radiation efficiency is defined in terms of the power that is radiated by a structure, the absolute square of the normal velocity on the surface integrated over that surface, and the characteristic impedance of the fluid facing the surface. The utilization of the radiation efficiency as a useful engineering quantity for describing the radiation from panel-like structures and for the estimation of the effectiveness of measures that may be used to control the radiated power from such structures, is questioned. Caution needs to be exercised in the use of the radiation efficiency for these purposes.

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## INTRODUCTION

The radiation efficiency of a panel-like structure immersed in a fluid is a useful physical quantity in estimating the radiative properties of such a structure. One would assume that the radiation efficiency relates directly to the ability of the panel-like structure to radiate acoustical power when excited by an external drive, i.e., the larger the radiation efficiency the more power efficient the structural radiator. This paper questions such general attributes to the radiation efficiency and examines others. The questioning is not made in order to challenge the use of the radiation efficiency, but rather to prevent its misuse. Thus, a number of questions may be asked:

- Does the radiation efficiency relate to the ability of the structure to radiate (acoustical) power?
- Is the radiation efficiency a useful engineering quantity?
- Can values of the radiation efficiency be beneficially tabulated for engineering purposes?
- Can similar structures be classified to possess equal radiation efficiencies either directly or by extrapolations? How useful are radiation class averages?

- Since radiation is a mechanism of damping in the structure, how are radiation and mechanical damping related?

Today active and/or passive controls of radiation from panel-like structures are being considered:

- What do these controls need to achieve?
- In particular, is the radiation efficiency a viable (relevant) quantity in such considerations?

To answer some of these questions, one may start with the definition of the radiation efficiency.

### RADIATION AND PARTIAL RADIATION EFFICIENCY OF A PANEL

The radiation efficiency  $\sigma(\omega)$  is defined in terms of the power  $\Pi_{\text{rad}}(\omega)$  that is radiated by a panel, the absolute square of the normal velocity  $|v(\underline{x}, \omega)|^2$  on the surface of the panel that is in contact with the fluid occupying the semi-infinite space in front, and the characteristic impedance ( $\rho c$ ) of the fluid

$$\Pi_{\text{rad}}(\omega) = (\rho c) \sigma(\omega) \int d\underline{x} |v(\underline{x}, \omega)|^2 ; \quad \underline{x} = \{x, y\} ; \quad d\underline{x} = dx dy , \quad (1)$$

where  $\underline{x}$  is the spatial variable in the plane of the panel and  $\omega$  is the frequency variable; see

Fig. 1 [1]. The partial radiation efficiency  $\sigma_y(\omega_2)$  is similarly defined in terms of the partial power  $\Pi_{y\text{rad}}(\omega_2)$  that is radiated by a panel, the absolute square of the normal velocity  $|\tilde{v}(x, \omega_2)|^2$  on the surface of the panel, and ( $\rho c$ ) of the fluid

$$\Pi_{y\text{rad}}(\omega_2) = (\rho c) \sigma_y(\omega_2) \int dx |\tilde{v}(x, \omega_2)|^2 ; \quad \omega_2 = \{k_y, \omega\} , \quad (2)$$

where the wavenumber variable  $k_y$  is the Fourier conjugate of the spatial variable  $y$ , and  $\tilde{v}(x, \omega_2)$  is the Fourier transform of  $v(\underline{x}, \omega)$  with respect to  $y$  [1]. The integration of the absolute square of the normal velocity in Equation (2) is only partially carried out as compared with Equation (1) where the integration is full. Computations with respect to  $\sigma_y(\omega_2)$  [Equation (2)] are obviously easier to perform than those with respect to  $\sigma(\omega)$  [Equation (1)]. Yet, the physical interpretations

often remain phenomenologically similar. This similarity, if exercised with caution, allows one to use the partial quantities and be availed of the simplicity that is afforded therein. The identities

$$\int d\mathbf{x} |v(\mathbf{x}, \omega)|^2 = \int d\mathbf{k}_y \left[ \int d\mathbf{k} |V(\mathbf{k}, \omega_2)|^2 \right] = \int_0^\infty \kappa d\kappa \int_{-\pi}^\pi d\phi |V[\kappa \sin(\phi), \kappa \cos(\phi), \omega]|^2 ;$$

$$\text{Tot} = \int d\mathbf{k} |V(\mathbf{k}, \omega)|^2 ; \quad \text{Tot}_y = \int d\mathbf{k} |V(\mathbf{k}, \omega_2)|^2 ; \quad \{\mathbf{k}, \omega\} \equiv \{\mathbf{k}, \omega_2\} , \quad (3)$$

are noted, where  $V(\mathbf{k}, \omega)$  is the Fourier transform of  $v(\mathbf{x}, \omega)$  with respect to  $\mathbf{x}$  and  $\mathbf{k}$  is the Fourier conjugate of  $\mathbf{x}$ . At times, as a matter of abbreviation when the dependent variables are obvious they may be suppressed; e.g.,  $\text{Tot}(\omega) = \text{Tot}$  and  $\text{Tot}_y(\omega_2) = \text{Tot}_y$ . The radiated and partial radiated power may be defined alternately to Equations (1) and (2) in the forms

$$\Pi_{\text{rad}}(\omega) = (\rho c) \int_0^{(\omega/c)} \kappa d\kappa \int_{-\pi}^\pi d\phi [1 - (\kappa c/\omega)^2]^{-1/2} |V(\kappa \sin \phi, \kappa \cos \phi, \omega)|^2$$

$$\simeq (\rho c) \text{ Supersonic portion of } \int d\mathbf{k} |V(\mathbf{k}, \omega)|^2 \equiv (\rho c) \text{ Sup} , \quad (4)$$

$$\Pi_{y\text{rad}}(\omega_2) = (\rho c/Y) \int_{-Y\omega/c}^{Y\omega/c} dk [1 - (kc/Y\omega)^2]^{-1/2} |V(\mathbf{k}, \omega_2)|^2$$

$$\simeq (\rho c) \text{ Supersonic portion of } \int d\mathbf{k} |V(\mathbf{k}, \omega_2)|^2 \equiv (\rho c) \text{ Sup}_y , \quad (5)$$

respectively, where  $c$  is the speed of sound in the fluid [1]. Thus, from Equations (1), (2), (4), and (5) one may generically state

$$\sigma(\omega) \simeq \text{Sup}/\text{Tot} ; \quad \text{Tot} = \text{Sup} + \text{Sub} ;$$

$$\text{Sub} = \text{Subsonic portion of } \int d\mathbf{k} |V(\mathbf{k}, \omega)|^2 , \quad (6)$$

$$\sigma_y(\omega_2) \simeq \text{Sup}_y/\text{Tot}_y ; \quad \text{Tot}_y = \text{Sup}_y + \text{Sub}_y ;$$

$$\text{Sub}_y = \text{Subsonic portion of } \int d\mathbf{k} |V(\mathbf{k}, \omega_2)|^2 . \quad (7)$$

It is apparent from Equations (6) and (7) that the radiation efficiency  $\sigma$  is substantially the ratio of the supersonic portion to the total integral of the absolute square of the normal velocity, and that the partial radiation efficiency  $\sigma_y$  is substantially the partial supersonic portion to the partial total

integral of the absolute square of the normal velocity on the radiating surface. The singular factors in the integrands of  $\Pi_{\text{rad}}$  and  $\Pi_{\text{rady}}$  do not play a decisive role in the determination of these quantities. Clearly the total integrated and the partial total integrated absolute square of the normal velocity on the radiating surface are composed of a supersonic portion and a subsonic portion each, as is stated in Equations (6) and (7), respectively. [Moreover, the analogy between  $\sigma$  and  $\sigma_y$  is apparent in Equations (1), (2), (3), and (4).] To answer some of the questions posed in the preceding section, these ratios need to be examined. The first step is to investigate the manner in which the normal velocity  $V(k, \omega) [= (V(k, \omega_2))]$  is established on the radiating surface of the structure. If the normal velocity, or even the absolute square of that normal velocity, on the radiating surface of a structure can be readily ascertained, there is no difficulty in ascertaining both the radiated power and the radiation efficiency. Indeed, in this case, the radiation efficiency is superfluous since the ultimate goal of defining the radiation efficiency is to derive the radiated power. However, an intimate knowledge of the absolute square of the normal velocity on a radiating surface is rarely available. What may be available is the total or even the partial total integration of the absolute square of the normal velocity over the radiating surface; namely,  $T_{\text{ot}}$  and  $T_{\text{oty}}$ . These quantities may be easily determined by a simple set of measurements and/or analytical procedures. The determination of  $S_{\text{up}}$  and  $S_{\text{upy}}$  is another matter, and yet they are the significant quantities for the determination of the radiation and partial radiation as well as the respected radiation efficiencies. In the next section an attempt is made to explore the ways and means for ascertaining  $S_{\text{up}}$  and  $S_{\text{upy}}$ . For this purpose a specific, and yet generic, example is presented. In this example an unribbed and a regularly ribbed panel, subjected to line drives, model the panel-like structures and the external driving systems, and the partial quantities are featured in the illustrations.



## NORMAL VELOCITY ON THE RADIATING SURFACE OF A STRUCTURE

The normal (spectral) velocity  $V(\underline{k}, \omega) [= (V(\underline{k}, \omega_2))]$  on the surface of a structure that is in contact with a fluid can be expressed formally in terms of the impulse response function  $\tilde{g}(\underline{k}|\underline{x}', \omega)$  [or equivalently  $\tilde{G}(\underline{k}|\underline{k}', \omega)$ ] and the external drive  $p_e(\underline{x}', \omega)$  [or equivalently  $P_e(\underline{k}', \omega)$ ] in the form

$$\begin{aligned} v(\underline{x}, \omega) &= \int g(\underline{x}|\underline{x}', \omega) d\underline{x}' p_e(\underline{x}', \omega) ; \\ V(\underline{k}, \omega) &= \int \tilde{g}(\underline{k}|\underline{x}', \omega) d\underline{x}' p_e(\underline{x}', \omega) \equiv \int G(\underline{k}|\underline{k}', \omega) d\underline{k}' P_e(\underline{k}', \omega) , \end{aligned} \quad (8)$$

where the spatial variable  $\underline{x}'$  is inclusive of  $\underline{x}$ ,  $\underline{k}$  is the Fourier conjugate of  $\underline{x}$ ,  $\underline{k}'$  is the Fourier conjugate of  $\underline{x}'$ , and the impulse response function is assumed pure in the sense that it is dependent only on quantities and parameters that describe the structure; it is independent of  $V(\underline{k}, \omega)$  [or equivalently  $v(\underline{x}, \omega)$ ] and of  $p_e(\underline{x}', \omega)$  [or equivalently  $P_e(\underline{k}', \omega)$ ]. Broadly, and at this stage in passing, passive controls modify the impulse response function, and active controls modify the external drive.<sup>1</sup> Note that these controls are placed with respect to  $\underline{x}'$  [or  $\underline{k}'$ ] and are not limited to span merely  $\underline{x}$  [or  $\underline{k}$ ], except when the spans of these variables happen to coincide. If driving machinery and machinery foundations are sitting atop the panel, the span of  $\underline{x}'$  and the span of  $\underline{x}$  do not coincide; the span of  $\underline{x}'$  exceeds that of  $\underline{x}$  by the spatial extent of the machinery foundations. However, in the examples cited in the paper, the coincidence of the spans of  $\underline{x}'$  and  $\underline{x}$  is assumed a priori. Typical distributions of the absolute square of the normal velocity on a panel, in response to a line drive, are shown in Figs. 2 and 3. The line drive is chosen with  $(bk_y) = 0$ , where  $b$  is a typical separation between adjacent ribs when ribs are attached to the panel; otherwise it is a convenient spatial scale [1]. Figure 2 depicts the flexural velocity for a frequency that lies above the critical frequency  $\omega_c$  or the longitudinal velocity at any frequency with  $(c_\ell/c) > 1$ , where  $c_\ell$  is the speed of the longitudinal free waves. The critical frequency  $\omega_c$  is defined with respect to the speed of sound  $c$  in the fluid. The specific values chosen for Fig. 2 are:  $(\omega/\omega_c) = 2$  or  $(c_\ell/c) = 2$ .

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<sup>1</sup>Equation (8) makes clear that, whole or in part, modification in the impulse response function may, at times, be conveniently accounted for by modifications in the drive and vice versa.

Other parameters which were chosen as standard for all the figures are: the panel is a plate,  $(\omega_c/c) b = 16$ ,  $(M/mb) = 0.3$ , and  $\eta_p = 2.5 \times 10^{-3}$ , where  $m$  is the mass per unit area of the panel,  $M$  is the mass per unit length of the rib, and  $\eta_p$  is the mechanical loss factor in the panel. In Fig. 3 the flexural velocity is depicted for a frequency  $\omega$  that lies below the critical frequency; e.g.,  $(\omega/\omega_c) \approx 0.2$ . It is observed that when the panel is ribbed, multiple resonance peaks (and anti-resonance valleys) occur, in the normal velocity, in addition to the two major peaks and two deep valleys. The two major peaks are resonance peaks that occur at the wavenumbers that are equal to the positive and negative value of the free wavenumber  $k_p$ ,  $k_p^2 = (\omega\omega_c/c^2)$ , and the two valleys appear at the wavenumbers that are equal to the positive and negative value of the sonic wavenumber  $(\omega/c)$ . These valleys are nonresonance and they occur in consequence of the extremely high (infinite) fluid loading at the sonic wavenumber. The additional resonance peaks and valleys are, of course, absent in the unribbed panel; the two major resonance peaks and the two deep valleys remain substantially intact; see Figs. 2 and 3. Usually the flexural, the longitudinal, and other types of responses contribute simultaneously to the normal velocity on the panel. For the sake of simplicity and brevity, subsequent consideration focuses merely on the flexural response. [Conceptually, based on this limited consideration, one may readily extend the arguments to encompass all those other types of responses.]

Figure 2 shows that above the critical frequency, the contribution to the integral of the absolute square of the normal velocity over the relevant spectral range is dominated by the supersonic components

$$Tot \approx Sup ; \quad Toty \approx Supy ; \quad (\omega/\omega_c) > 1 . \quad (9)$$

From Equations (6) through (9) one obtains

$$\sigma \approx 1 ; \quad \sigma_y \approx 1 ; \quad (\omega/\omega_c) > 1 . \quad (10)$$

It is thus realized that for the flexural response above the critical frequency, the radiation efficiency is a straightforward quantity on several accounts: because of its unit identity and, importantly, and

as already implied, because Tot and even Toty are relatively easy to determine by a simple set of measurements and/or analytical procedures. [cf. Equation (8).] Equations (1) through (10) make it clear that above the critical frequency, direct relationships exist between the radiated powers  $\Pi_{\text{rad}}$  and  $\Pi_{y\text{rad}}$  and the respective values of Tot and Toty. The unity for the radiation efficiencies, as stated in Equation (10), ensures the existence of those relationships.

On the other hand, it is observed in Fig. 3 that below the critical frequency the contribution to the total and partial total integral of the absolute square of the normal velocity is not dominated by the supersonic components. In fact, the contribution to the integral of the absolute square of the normal velocity is dominated largely by the subsonic components; i.e., below the critical frequency

$$\text{Sup} \lesssim (1/2) \text{Tot} ; \quad \text{Supy} \lesssim (1/2) \text{Toty} ; \quad (\omega/\omega_c) < 1 . \quad (11)$$

From Equations (6), (7), and (11) one obtains

$$\sigma \lesssim (1/2) ; \quad \sigma_y \lesssim (1/2) ; \quad (\omega/\omega_c) < 1 . \quad (12)$$

As already twice implied, determining Tot or even Toty is a relatively simple task. However, extracting the values of Sup and Supy, is usually not an easy task, especially when the panel possesses localized surface impedance nonuniformities, such as ribs, that cause resonances. While the details of the peaks in the supersonic range may not be significant here, they play a significant role in contributing to the integrals that determine Sup and Supy. To measure Sup or Supy in the presence of the much larger Tot or Toty, respectively, is a mean task to perform. When Sup and Supy assume the role of the signals, Sub and Suby assume the role of the noises, respectively. Below the critical frequency, the latter quantities dominate the former. Moreover, Sup and Supy are dominated, by definition, by components that are spatially large scale with respect to the sonic wavenumber; i.e., components that lie in the low wavenumber range, below the sonic wavenumber. These components are thus intrinsically more difficult to measure than those spatially small scale components that are contributing to Sub and Suby. To compound the difficulty, the distribution and nature of the additional resonance peaks (and valleys) in the

response of the panel, are closely linked to the distribution and nature of the structural components and their couplings and the external drive systems that excite them; e.g., the ribs and their interactions via the panel, the positioning of the external line drive, etc. Worse, the disposition of these additional resonance peaks and (anti-resonance) valleys may be sensitive even to *minor* changes in the features of a "structural-drive" system. For example, a component in the structure that is defined by the spatial parameter  $L$  and the loss factor  $\eta_p$ , undergoes a *minor* change if  $L$  varies by  $\Delta L$  and  $\eta_p$  by  $\Delta\eta_p$  so that  $(k_p\Delta L) \ll 1$ , and  $(Lk_p\Delta\eta_p) \ll 1$ , where  $k_p$  is the free wavenumber associated with this component. Variations of this kind in the parameters that describe the structure and the external drive system may strongly influence the disposition of the additional resonance peaks and valleys if they are present. This strong influence is depicted in Figs. 4 and 5. The standard response; e.g., Fig. 3, is compared with responses in which changes in the standard values of parameters are introduced. In Fig. 4 the separation between adjacent ribs is changed, and in Fig. 5 the position of the application of the line drive is changed. It is observed that even in this simple and regularly constructed structure, the influence of *minor* changes in the separation between adjacent ribs and the positioning of the external drive may be quite strong. As already indicated, below the critical frequency the resonance peaks in the supersonic range dominate the contribution to  $Sup$  and  $Sup_y$ . To summarize the complexity that exists below the critical frequency: the supersonic components are spatially large and not easily deciphered in the presence of the more numerous spatially smaller subsonic components; yet, the peaks in the supersonic components may be sensitive to *minor* structural details. In the absence of nonuniformities, the situation is much less complicated; there are no additional peaks to be concerned with, and the supersonic range is more robust to changes in the structure; e.g., increase in the mechanical damping hardly changes the response in the supersonic range of a uniform panel responding below the critical frequency. This statement is illustrated and supported in Fig. 6. In

contrast, the mechanical damping has a pronounced effect on the resonance peaks (and valleys), even those that lie in the supersonic range of spectral space.<sup>2</sup> This statement is illustrated and supported in Figs. 7 and 8. The difference between Fig. 7 and Fig. 8 is in the positioning of the external drive [cf. Fig. 5].

### RADIATION EFFICIENCY BELOW THE CRITICAL FREQUENCY

Above the critical frequency, the radiation efficiency is substantially equal to unity and unity requires no special consideration; see Figs. 9 and 10. At and in the vicinity of the critical frequency, the nature of the radiation efficiency and the nature of the radiated power require special treatment; however, this treatment lies outside the scope of this paper [1].

It is apparent that below the critical frequency the radiation efficiency is below unity; see Figs. 9 and 10. As argued, the radiation efficiency is less than unity because  $T_{ot}$  and  $T_{ot_y}$  on the radiating surface are not dominated by the supersonic components. To ascertain the radiated power and/or the radiation efficiency, the portion that is contributed by the supersonic components to these integrals needs to be estimated. Figure 9 depicts such an evaluation for an unribbed uniform panel. The evaluation is stated in terms of the partial radiation efficiency. Does the (partial) radiation efficiency relate to the ability of the structure to radiate (acoustical) power? It was stated earlier that  $Sup$  and  $Sup_y$  are substantially unaffected by mechanical damping; see Fig. 6. It is concluded that the radiated and partial radiated power are similarly unaffected by this damping. However, the radiation and partial radiation efficiency are strongly affected;  $\sigma$  and  $\sigma_y$  increase with

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<sup>2</sup>One is aware that components, in the response, that lie in the supersonic range are damped by radiation, in addition to the mechanical damping. Therefore, when mechanical damping is increased, it is destined to be relatively more effective on components that reside in the subsonic range than on those residing in the supersonic range. However, one should also be aware that resonances usually take place for reasons that transcend the mere damping of individual constituent spectral components; spectral components will adjust their positions of residence, and even their affiliation if necessary, to accommodate the response of the structure as a whole.

increase in mechanical damping. This increase in  $\sigma_y$  is illustrated in Fig. 9. Does the increase in the radiation efficiency or the partial radiation efficiency imply that the structure radiates more power? In this case, no; it merely implies that the flexural Sub and Suby are decreased by mechanical damping; e.g., see Fig. 6. Thus, as this example amply demonstrates, the radiation efficiency alone is not sufficient to specify the radiative properties of a panel-like structure below the critical frequency. It emerges that, in this simple case of a uniform panel, two panels that are identical except for a difference in the applied mechanical damping, yield different radiation efficiencies. The panel with *less* mechanical damping yields the *lower* radiation efficiency. Yet, to a given drive, the radiated powers by these two structures are substantially the same. The example indicates that "apparently similar structures *cannot* be classified to possess equal radiation efficiencies."

Figure 10 depicts phenomenologically a more realistic situation. First, the partial radiation efficiency below the critical frequency is not smooth with frequency, as in Fig. 9. The uneven values of the partial radiation efficiency, as a function of frequency, have to do with the periodicity of the attached ribs [1]. [The excursions in the unevenness are expected to be less pronounced when the periodicity is disturbed.] As displayed in Figs. 2 and 3, the ribs (the nonuniformities in the surface impedance of the uniform panel) induce additional resonance peaks (and valleys) in the absolute square of the normal velocity on the radiating surface. The additional resonance peaks below the critical frequency, especially those residing in the supersonic range, contribute dominantly to the radiated power from the panel. The contributions to the radiated power tend to be large from those supersonic regions that are occupied by these additional resonance peaks. The presence of these peaks, their locations, and their sizes change with frequency. It was argued earlier that further to the sensitivity of these peaks to changes in frequency, these peaks are also sensitive to changes in the parameters that define the radiating structure and the external drive system. The sensitivity involves even *minor* changes in this parametric definition. Therefore, the radiated power is likewise sensitive to these changes in the frequency and to *minor* changes in the parameters that define the structure-drive system. On the other hand, flexural Tot and Toty are

governed largely by the two major peaks which are not so sensitive to these changes. It is thus concluded that the radiation and partial radiation efficiency, below the critical frequency, would exhibit the kind of peaks and valleys displayed generically in Fig. 10. The peaks and valleys in Fig. 10 can be directly related to the changes in the resonance peaks and valleys that occur in the absolute square of the flexural velocity with changes in frequency [1]. In particular, it is argued that these kind of peaks and valleys would also be sensitive to even *minor* changes in the mechanical-drive system of a (complex) radiating structure. [cf. Figs. 3 through 5, 7, 8, and 10.] It follows that, below the critical frequency, the (partial) radiation efficiencies of two nominally identical structures may, in details, be very different due to these sensitivities; e.g., again, see Figs. 3 through 5, 7, 8, and 10. Some of these sensitivities may be dulled by averaging over frequency bands and/or ensemble of nominally identical structures. This kind of averaging may be used to derive a "radiation class average." Although useful, these types of procedures occasionally and unexpectedly cause poor estimates, whether or not these estimates are backed by measurements and/or by analytical procedures. Finally, one may investigate the influence of mechanical damping on the radiated power and the radiation efficiency of a ribbed panel. The resonance peaks (and anti-resonance valleys) are, by nature, sensitive to damping. Therefore, if the radiated power is contributed largely by resonance peaks, an increase in mechanical damping would usually yield a decrease in the radiated power. Below the critical frequency there always exists at least two resonance peaks in the subsonic range. An increase in mechanical damping would cause the usual decrease in density of subsonic components residing in those spectral regions that were occupied by resonance peaks when damping was lower; e.g., see Figs. 7 and 8.<sup>2</sup> The decrease in the density of components that lie within the major peaks will be dominant. Therefore, one would expect that below the critical frequency an increase in the radiation efficiency will usually result from increase in the mechanical damping; e.g., see Fig. 10. However, like the differences between the radiation efficiencies of an unribbed and a ribbed panel, the increase in the radiation efficiency with increase in mechanical damping would be more erratic and uneven in the latter case. In spite of this, an increase in the mechanical damping tends to smooth out the

unevenness in the radiation efficiency of a ribbed panel; e.g., see Fig. 10. Again, the cavalier use of the radiation efficiency as a quantity relevant to the radiative properties of a radiating structure is flagged.

The application of mechanical damping to a radiating structure is, in a way, already the employment of a passive device designed to control the radiated power by the structure. The understanding and caution that are required in assessing and estimating the usefulness of even this common passive device, in terms of the radiation efficiency, is hopefully clear. When one turns to the introduction (application) of other, less common, and/or more sophisticated devices that are designed to control the radiated power from panel-like structures, the use of the radiation efficiency demands even more understanding and caution. Only a synopsis of that demand is treated in the next section.

## CONTROL OF THE RADIATED POWER VERSUS THAT OF THE RADIATION EFFICIENCY

Equation (8) is recalled. To control (reduce) the radiation (to the far field) one needs modify the impulse response function  $\tilde{g}(\mathbf{k}|\mathbf{x}', \omega)$  [ $\equiv G(\mathbf{k}|\mathbf{k}', \omega)$ ] and/or the external drive  $p_e(\mathbf{x}', \omega)$  [ $\equiv P_e(\mathbf{k}', \omega)$ ] in such a manner that Sup (or Supy) on the radiating surface is definitively controlled (reduced).<sup>1</sup> As Equations (4) and (5) indicate, the relationship between the control (reduction) of the power and the control (reduction) of the supersonic portion of the absolute square of the normal velocity is direct. On the other hand, any change (e.g., a reduction in the subsonic portion of the absolute square of the normal velocity) has no influence on the radiated power. Equations (6) and (7) show that a direct relationship does not necessarily exist between the control (reduction) of the radiated power and the possible changes in the radiation efficiency due to the change in Sup (or Supy) induced by the various control measures. The absence of a direct relationship of this kind prompted the questioning posed in the introduction to this paper. In this connection, it should be pointed out that if the generation of the normal velocity on the radiating surface of the structure could be selected (fixed) directly, not via Equation (8), then the radiation



efficiency could also be manipulated directly and the questioning would become superfluous. Often, however, this is not the case. The control that one can usually exercise is limited to the manipulations of the impulse response function  $\tilde{g}$  [or equivalently  $G$ ] and/or  $\tilde{p}_e$  [or equivalently  $P_e$ ] and not of  $V(k, \omega)$ .

It was established in the preceding section that a control device that reduces the supersonic portion of the absolute square of the normal velocity on the radiating surface results in a substantially corresponding reduction in the radiated power to the far field. It is noted, however, that the radiation efficiency, in consequence of implementing this radiation control device, may either *decrease, remain unchanged, or increase*, depending on the accompanied change in the subsonic portion of the absolute square of the normal velocity on the radiating surface. Again, this accompanied change, it is noted, has no influence on the radiated power. Therefore, the radiation efficiency alone may not be a reasonable quantity with which to assess the success or failure of an active and/or a passive control of the radiated power. In conjunction with other indicators, the radiation efficiency may be of some use [2]. For example, if the radiated power is reduced and the radiation efficiency is increased, one may conclude that the subsonic portion of the integral of the absolute square of the normal velocity, i.e.,  $Sub$ , is decreased, by the control device, proportionately more than  $Sup$ . In certain situations such information may be useful [2].

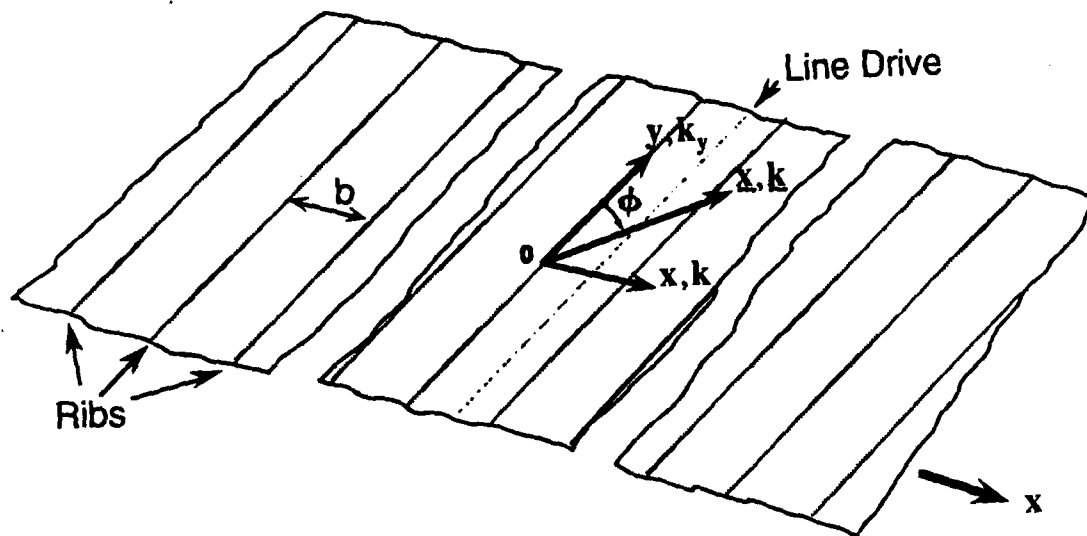


Fig. 1. A ribbed panel and the coordinate system.



Fig. 2. The 10 log of the absolute square of the normal velocity on a fluid loaded plate as a function of the normalized wavenumber. The velocity is generated by a line drive applied at  $x_s = 0.3b$ , where  $b$  is the separation between adjacent ribs. Depicted is either the flexural response above the critical frequency  $\omega_c$ ,  $(\omega/\omega_c) = 2.0$  (the critical frequency is with respect to the loading fluid of density  $\rho$  and speed of sound  $c$ ) or a longitudinal response that is governed by a free wave speed  $c_\ell$  such that  $(c/c_\ell) = 2.0$ . Other standard parameters are  $(\omega/c)b = 16$ ,  $\eta_p = 2.5 \times 10^{-3}$ , and  $(bk_y) = 0$ .

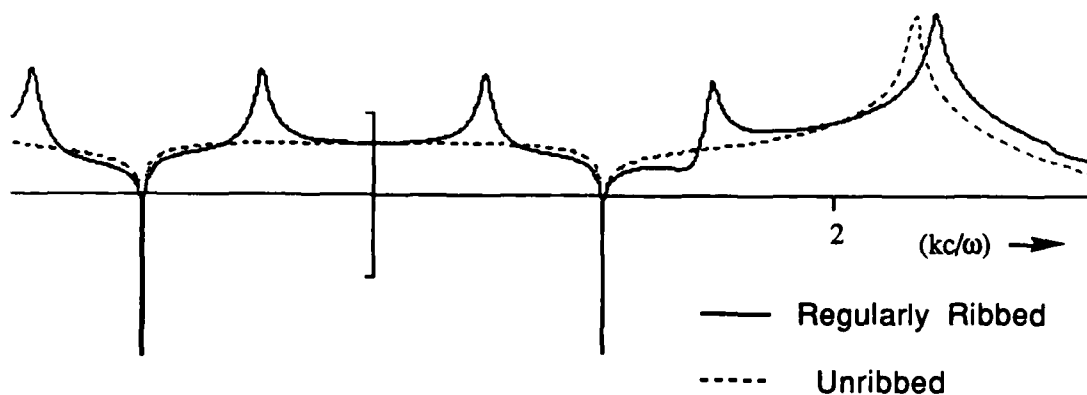


Fig. 3. The same as Figure 2 except that the response is for a flexural wave below the critical frequency,  $(\omega/\omega_c) = 0.2$ .

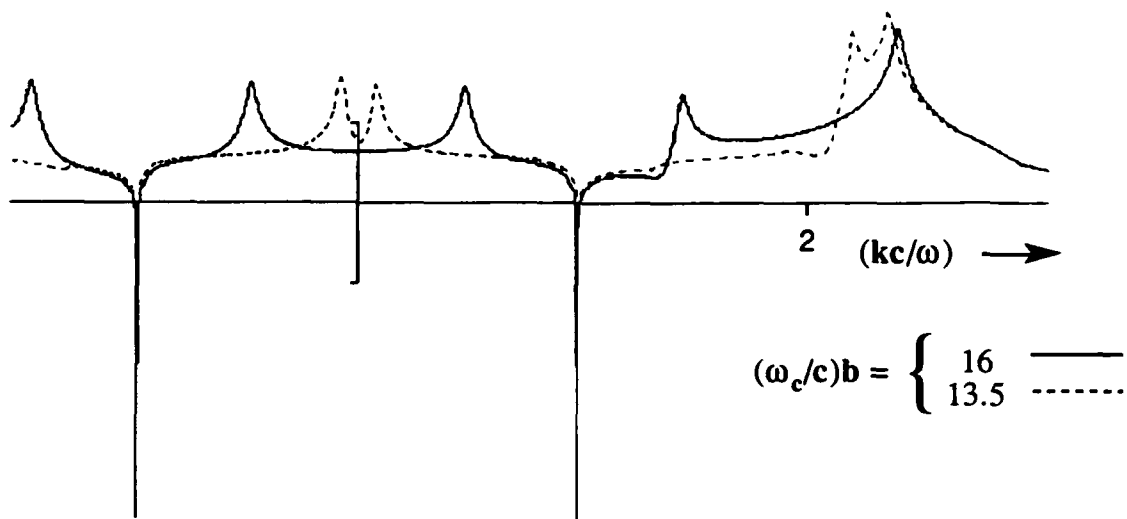


Fig. 4. The same as Figure 3 except that the parameter  $(\omega_c/c)b$  is changed as indicated.

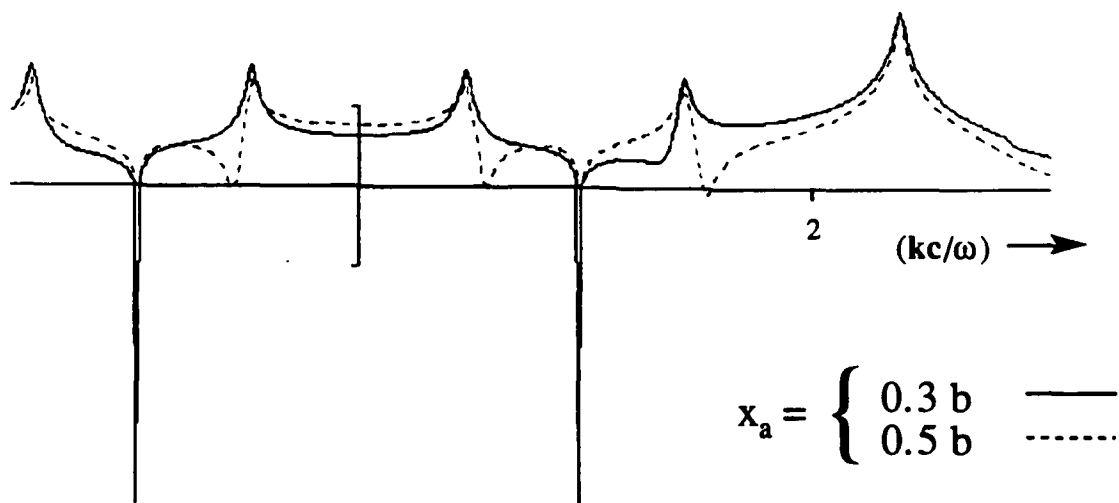


Fig. 5. The same as Figure 3 except that the location of the drive is changed as indicated.

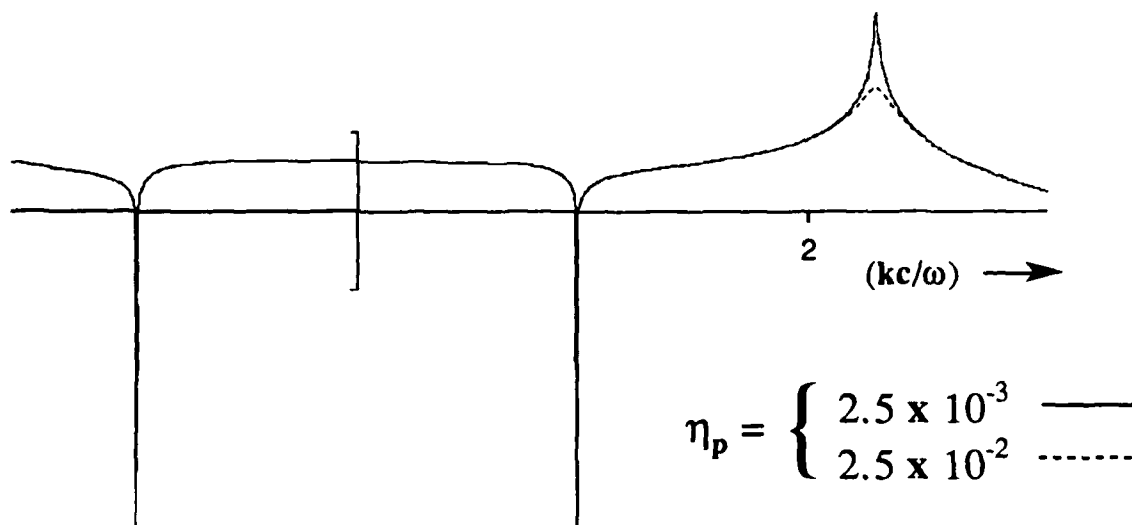


Fig. 6. The same as Figure 3 for the unribbed plate except that the loss factor is varied as indicated.

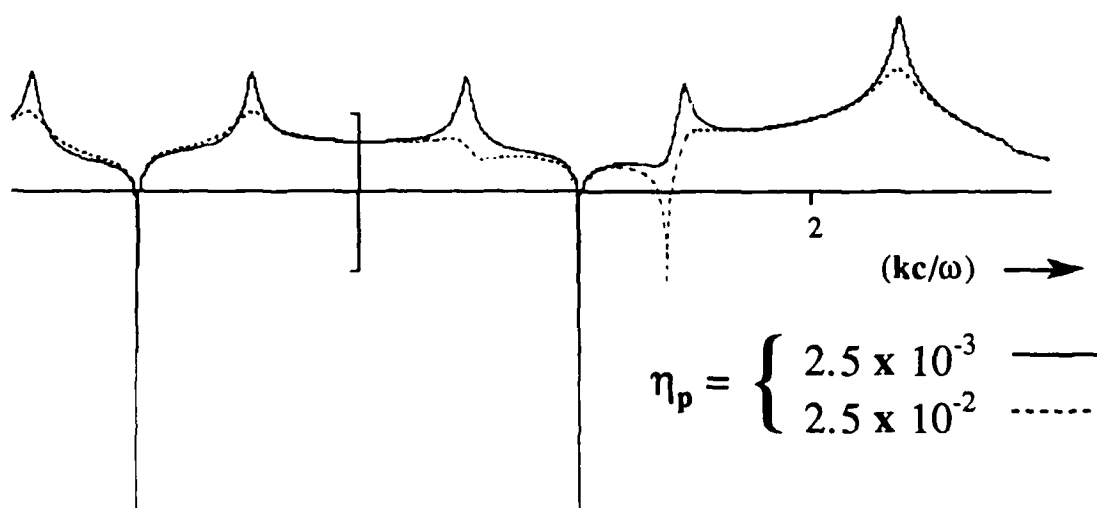


Fig. 7. The same as Figure 3 for the ribbed plate except that the loss factor is varied.

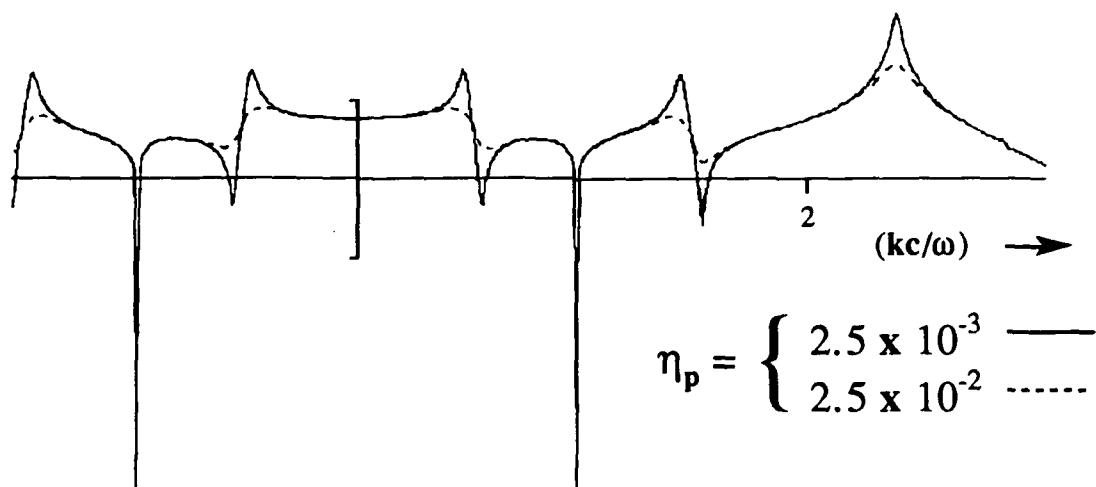


Fig. 8. The same as Figure 7 except that the plate is driven at  $x_a = 0.5b$  rather than the standard  $x_a = 0.3b$

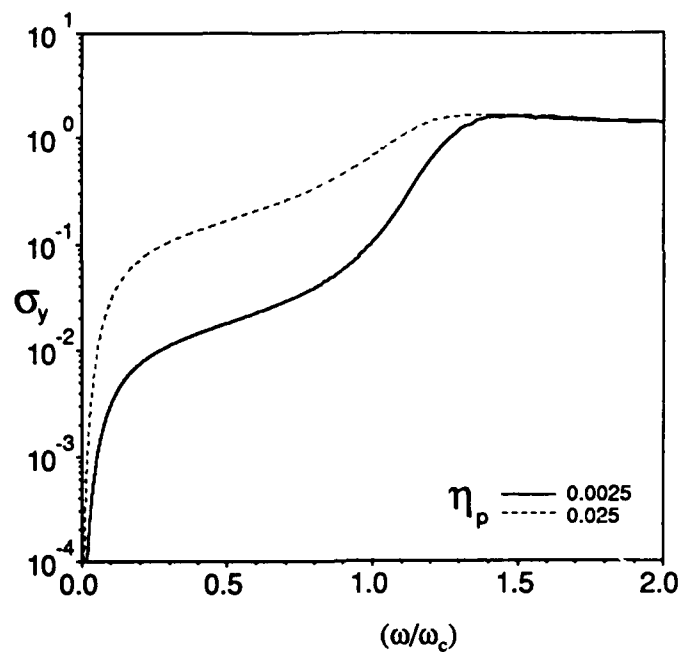


Fig. 9. The partial radiation efficiency  $\sigma_y(\omega_2)$ ,  $\omega_2 = \{k_y, \omega\}$ , of a fluid loaded unribbed plate excited by a line drive applied at  $x_a = 0.3b$  and with  $(bk_y) = 0$ . [cf. Figures 1 through 3.]

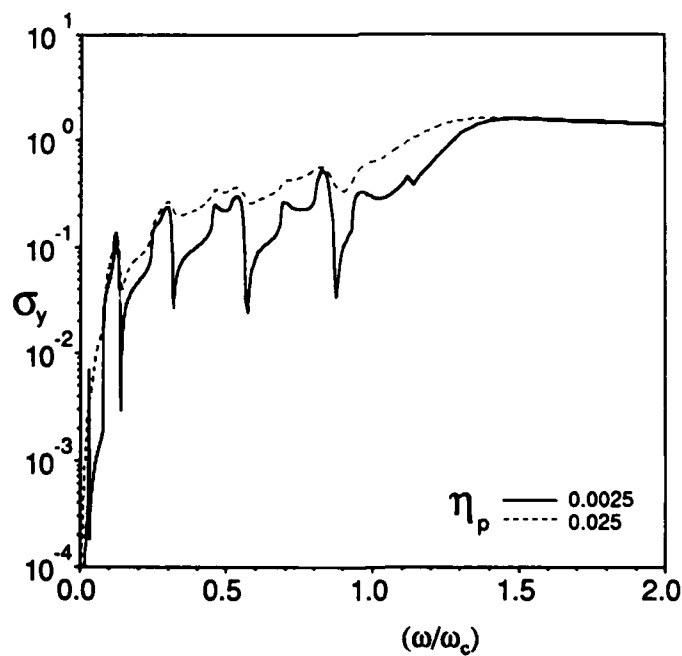


Fig. 10. The same as Figure 9 except that the plate is regularly ribbed.

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